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(71) Applicant: AWARE, INC. [US/US]; 40 Middlesex Turnpike, Bedford, MA 01730 (US).

(72) Inventors: TZANNES, Marcos; Unit #53, 665 Lowell Street, Lexington, MA 02173 (US). KECHRIOTIS, George; 34 Hamilton Road #2, Arlington, MA 02174 (US). WU, Pui; 41A Tremont Street, Malden, MA 01248 (US).

(74) Agents: O'DONNELL, Martin, J. et al.; Cesari and McKenna, LLP, 30 Rowes Wharf, Boston, MA 02110 (US).

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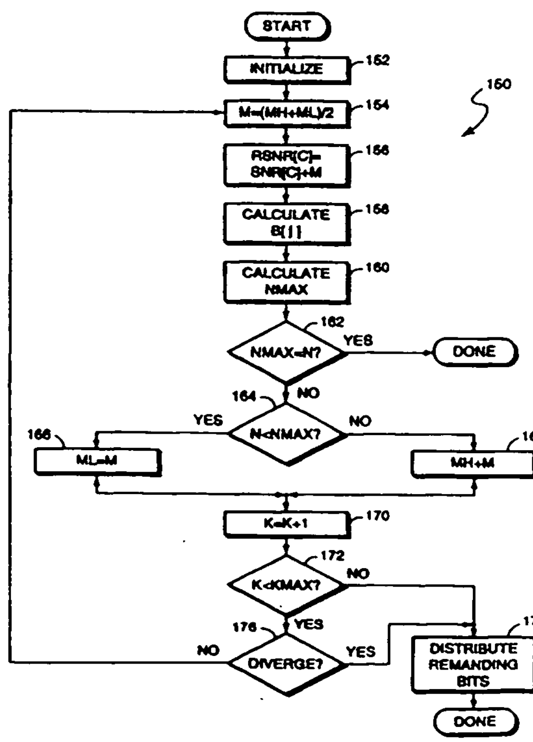
(54) Title: ADAPTIVE BIT ALLOCATION FOR VARIABLE BANDWIDTH MULTICARRIER COMMUNICATION

(57) Abstract

Data is distributed among the channels of an asynchronous data subscriber loop (ADSL) communications system in accordance with an adaptive algorithm which from time to time measures the signal to noise ratio of the various channels and finds a margin for each channel dependent on achievement (where possible) of a given bit error rate and a desired data transmission rate. The margin distribution is achieved by augmenting the constellation signal to noise ratio to enhance computational efficiency and allow redetermination of bit allocation tables during transmission as necessary. Pairs of bit allocation tables are maintained at the transmitter and receiver and one table of each pair at the transmitter and receiver is updated while the other pair is in use for controlling communication.



ADAPTIVE BIT ALLOCATION FOR VARIABLE BANDWIDTH MULTICARRIER COMMUNICATION

TECHNICAL FIELD

This application relates to the field of electronic communication and more particularly to the field of multiband digital signal communication.

BACKGROUND OF THE INVENTION

Conventional multicarrier digital communication is a technique for transmitting and receiving digital signals using a plurality carriers (subchannels) having different frequencies. Each of the subchannels is used to communicate a different portion of the signal. The transmitter divides the signal into a number of components, assigns each component to a specific one of the carriers, encodes each of the carriers according to the component assigned thereto, and transmits each of the carriers. The receiver decodes each received carriers and reconstructs the signal.

The maximum amount of information that can be encoded onto a particular subcarrier is a function of the signal to noise ratio of the communication channel with respect to that subcarrier. The signal to noise ratio of a communication channel can vary according to frequency so that the maximum amount of information that can be encoded onto one carrier may be different than the maximum amount of information that can be encoded onto another carrier.

Bit loading is a technique for assigning bits to subchannels according to each subchannel's signal to noise ratio. A bit loading algorithm provides a bit allocation table that indicates the amount of information (in bits) that is to be encoded on each of the carriers. That is, for a multicarrier communication system with J carriers, a bit allocation table B[j] indicates, for each j = 1 to J, the amount of information that is to be encoded onto each of the J carriers.

Shaping the transmission to match the channel characteristics is known. For example, a technique known as "water pouring" was introduced by Gallager in 1968

when the bit allocation table is changed, it is necessary to synchronize use of the new table with both the transmitter and the receiver. If the transmitter and the receiver use different bit allocation tables at any time, the communications link will suffer significant errors in those subchannels in which the bit allocation tables do not agree.

In addition, determining a new bit allocation table can be time consuming, especially if the bit loading algorithm is computationally intensive, such as that disclosed by Hughes-Hartogs where the bit allocation table is constructed one bit at a time. If the bit allocation table is to be calculated many times during communication between the transmitter and receiver, then spending a relatively long amount of time recalculating the bit allocation table (and hence not communicating data) is undesirable.

One solution is to simply not change the bit loading table after initialization. However, this may be unacceptable in cases where the communication channel signal to noise ratio changes during data transmission. Accordingly, it is desirable to be able to determine a bit loading table relatively quickly and to be able to synchronize use of the new table by the transmitter and the receiver.

SUMMARY OF THE INVENTION

In accordance with the present invention, a pair of bit allocation tables are maintained at both the transmitter and the receiver. These tables are updated as needed, using measurements of the signal to noise ratio performed on known data transmitted to the receiver in a control frame separate from the data frame. The transmitter signals the receiver as to which of the two tables is to be used for subsequent communication. Preferably, this is done by transmitting a flag from the transmitter to the receiver at some point during the data transmission; this causes the receiver to thereafter switch the bit loading table it is using for communication to synchronize with the corresponding table at the transmitter.

In the preferred embodiment of the invention, although the invention is not restricted thereto, 69 "frames" of 245.5 microseconds duration each are used to form a "superframe" of 16.94 milliseconds. The first frame of each superframe comprises a control frame that is used to transmit a standard (known) data set from the transmitter to the receiver; the remaining frames contain data. The receiver measures the signal to

$SNR_a[c_j] = SNR[c_j] + M$, and this value is used to determine (e.g., by table lookup as described above) the number of bits that can be transmitted over a channel. By augmenting the constellation signal to noise ratio, $SNR[c_j]$, rather than the channel signal to noise ratio, SNR_j, fewer additions are required, since the range of constellation sizes (e.g., $c_j = 1 \ldots 15$) is typically smaller than the range of channels (e.g., $j = 1 \ldots 256$).

As long as the amount of data that can be transmitted over the channels in a given interval differs (as determined by the calculations just described) from the amount of data desired to be transmitted in that interval, i.e., $N_{max} \neq N$, and assuming that certain other exit conditions have not been satisfied, the receiver cycles through a loop that repeatedly adjusts the margin M and recalculates N_{max}. To do this, the receiver sets a high margin threshold M_H and a low margin threshold M_L. During those superframes in which the bit allocation table is to be recalculated, the high threshold and low threshold margins are initialized to either a first state ($M_H = 0$, $M_L = (10/J)*[N_{max} - N]$) or a second state ($M_L = 0$, $M_H = (10/J)*[N_{max} - N]$) dependent on whether N_{max} is greater than N or less than N.

Thereafter, in each iteration, either the high or the low margin is adjusted in the search for the condition in which $N_{max} = N$. Specifically, at the beginning of subsequent (non-initialization) iterations, the margin is set to the average of the high and low margin thresholds, $M = (M_H + M_L)/2$, and the augmented constellation signal to noise ratio $SNR_a[c_j]$, the bit allocation table B[j], and the calculated capacity N_{max} are determined.

If the calculated capacity exceeds the desired capacity, i.e., $N_{max} > N$, the receiver increases the low margin threshold margin to M, i.e., it sets $M_L = M$. If the calculated capacity is less than the desired capacity, i.e., $N_{max} < N$, the receiver decreases the high threshold, i.e., it sets $M_H = M$. The iteration then repeats.

The receiver exits from the loop on the occurrence of any of several conditions. A first occurs when it is determined that $N_{max} = N$. This is the desired solution, and represents an optimum equal distribution of margin over the communication channels.

In particular, the tables B[j] define, for each channel j, the number of bits that can reliably be transmitted over a particular channel at a given bit error rate at the specific signal to noise ratio measured for that channel. These tables are determined as described in detail herein, and may vary from time to time during the course of a transmission.

At any given time, a single table, e.g., table 12, is used for transmission at the transmitter, and a corresponding table, e.g., table 20, is used for reception at the receiver. These tables are images of each other, i.e., contain the same data, and are used in pairs, so that reliable communication can occur. Similarly, tables 14 and 22 are images of each other and are used in pairs.

A table control unit 24 at the receiver controls the formation of the bit allocation tables 12, 14, 20, and 22. It measures the signal to noise ratio on each of the channels f_1, f_2, ...f_J, compares the measured values with predetermined values defining the bit capacity of a channel at given signal to noise values, augmented with noise margins as described herein, and thus determines the bit allocation for each channel. The allocations so defined are stored in the tables 20 and 22 at the receiver. They are also transmitted back to the transmitter, e.g., via a control channel 26, and are there stored as the tables 12 and 14, respectively. After initial loading, the transmission is advantageously arranged such that only updated tables are transmitted back to the transmitter.

At the transmitter 10, a table switch unit 28 selects which of the two table pairs (12, 20; 14, 22) are to be used in a given transmission and reception. Typically, a given pair will continue in use until the communication conditions change sufficiently that the bit allocations among the channels change. At that time, a new table must be formed at the receiver, and communicated to the transmitter. When this occurs, the table switch unit 28 typically will switch to the new table for subsequent transmissions. When it does so, it transmits a flag to the receiver that indicates that a switch to the alternative pair is to take place. This switch will usually be made effective as of the next superframe, but may, by prearrangement with the receiver, be made effective at some agreed upon point after that.

Fig. 2 is a diagram of a superframe 30. It is formed from a control frame 32 and a number of data frames 34. During the control frame interval, the transmitter sends to the receiver a known signal from which the receiver can measure the signal to noise ratio

number of bits transmitted. Increasing the number of discrete amplitudes and/or phases associated with a particular carrier (i.e., increasing the constellation size) increases the likelihood of bit errors. The BER increases with increasing constellation size because, as the number of discrete amplitudes and/or phases increases, the magnitude of the difference between discrete phases and/or amplitudes decreases and hence the ability of the receiver to distinguish between different phase and/or amplitude values decreases.

The relationship between BER and SNR is well-known in the art of multicarrier communication. Tables are available that show the minimum SNR that can support a BER of a fixed amount or less for a given constellation size. For example, the table shown below, $SNR[c_j]$, a constellation signal to noise ratio, indicates the minimum SNR needed to transmit a constellation having the indicated size in order to obtain an expected BER of 10^{-7} (i.e., an error of one bit per every 10^7 bits that are transmitted.) Note that as the constellation size increases, the minimum required SNR also increases.

Constellation size c (in bits)	SNR requirement
2	14 dB
3	19 dB
4	21 dB
5	24 dB

Referring to Fig. 4, a graph 110 illustrates a relationship between SNR and frequency for a communication channel transmitting a multicarrier signal having carriers between frequencies f_I and f_J. A vertical axis 112 of the graph 110 represents SNR. A horizontal axis 114 of the graph 110 represents frequency in a manner similar to that illustrated in connection with the horizontal axis 102 of the graph 100 of Fig. 3.

A plot 116 shows the relationship between SNR and frequency for the frequencies between f_I and f_J, the lowest and highest (respectively) carrier frequencies for the multicarrier frequency signal. The plot 116 illustrates that the SNR varies according to frequency so that, for example, the SNR at frequency f_m is lower than the SNR at frequency f_n. Based on the table shown above, it is possible that, for a given BER, the

the minimum SNR requirement of 21 dB. Similarly, it is possible to use less than the maximum supported constellation size at a particular carrier frequency. For example, although the plot 122 shows that a carrier at the frequency f_a will support a constellation size of five bits (since the SNR at f_a is 24 dB), it is possible to encode the carrier at the frequency f_a with only three bits. In that case, the margin at the frequency f_a is the difference between the transmission channel SNR at f_a (24 dB) and the SNR required to support a constellation of three bits at frequency f_a (19 dB). Accordingly, the margin at frequency f_a is 5 dB.

In instances where the multicarrier signal is used to transmit the maximum number of data bits, then the SNR of the communication channel is first measured and then each carrier is set to the maximum supported constellation size. However, in many applications, the multicarrier signal is used to transmit less than the maximum possible number of bits. In those cases, it is advantageous to maximize the overall margin of the signal to thus reduce the error rate. This can be illustrated by a simple example:

Assume a two-channel multicarrier signal has a maximum constellation size of five bits for the first carrier and four bits for the second carrier. Further assume that it is desirable to use the signal to transmit six bits. One way to allocate the bits among the two carriers is to use the first carrier to transmit five bits and the second carrier to transmit one bit. In that case, however, the margin for the first carrier is relatively small while the margin for the second carrier is relatively large. There will be many more errors for bits transmitted via the first carrier than bits transmitted via the second carrier and, since most of the bits are being transmitted via the first carrier anyway, then the overall error rate of the signal, while below the target BER, is still higher than it has to be in this case. A more advantageous way to allocate the bits might be to allocate three bits to each of the two carriers. In that case, both of the carriers operate with a relatively large margin and the overall error rate of the signal is reduced.

Of course, in many multicarrier communication applications, there are hundreds of carriers and hundreds to thousands of bits that are transmitted. In addition, it is necessary to allocate the bits in a relatively rapid manner since time spent allocating bits is time not spent communicating information. Furthermore, it may be necessary to reallo-

If it is determined at the test step 162 that N_{max} does not equal N, then processing transfers from the test step 162 to a test step 164. Note that if N is less than N_{max}, then the margin can be increased (in order to decrease N_{max}) in the next iteration. Similarly, if N is not less than N_{max}, then the margin is too large and needs to be decreased in the next iteration. If it is determined at the test step 164 that N is less than N_{max}, the control transfers from the test step 164 to a step 166 where M_L, the low-bound on the margin, is set equal to M. Setting M_L equal to M effectively increases M_L, causing an increase in the value of the margin, M, that will be calculated on the next iteration at the step 154.

Conversely, if it is determined at the step 164 that N is not less than N_{max}, then control transfers from the step 164 to a step 168 where M_H, the high-bound on the margin is set equal to M. This effectively decreases the value of M_H, thus causing the value of M to decrease when M is calculated at the step 154 on the next iteration.

Control transfers from either the step 166 or step 168 to a step 170 where the iteration counter, k, is incremented. Following the step 170 is a test step 172 which determines if the iteration counter is less than the maximum allowable value for the iteration counter, K_{max}. The iteration counter, k, is used to ensure that the algorithm will terminate after a certain number of iterations even if the terminating condition at the step 162 (i.e., $N_{max} = N$) is never met. In a preferred embodiment, K_{max} equals 16.

If it is determined at the test step 172 that k is not less than K_{max}, then control transfers from the step 172 to a step 174 where the remaining bits are either removed or added to the bit table, B[j], as appropriate. Bits are added or removed at the step 174 in a random or pseudo random manner so that the sum of all allocated bits in the table B[j], equals N, the number of bits that are to be transmitted via the multichannel signal. Note that in this instance, there is no guarantee that each of the carriers has a margin of at least M. The step 174 is simply executed in order to finalize the allocation process if the algorithm is unable to meet the termination condition at the step 162.

If it is determined at the test step 172 that the iteration counter, k, is less than the predetermined maximum value for the iteration counter, then control transfers from the

B[j], with a margin of zero. Following the step 186 is a step 188 where N_{max} is calculated. The step 188 is similar to the step 160 discussed above in connection with the flow chart 150 of FIG. 6; N_{max} is simply the sum of all the entries in the bit table, B[j].

Following the step 188 is a step 190 where it is determined if N_{max} equals N. If N_{max} does equal N at the step 190, then processing is complete for the entire algorithm (not just the initialization portion) since the channel will only support N_{max} bits of transmission. That is, if N_{max} equals N at the step 190, there is no point in continuing with the algorithm and calculating a margin since, by default, the channel can transmit no more than N bits.

If it is determined at the test step 190 that N_{max} does not equal N, then control transfers from the step 190 to a test step 192 where it is determined if N is less than N_{max}. Note that if N is not less than N_{max} at the step 192, then the channel will not support transmission of N bits at the BER used to construct the SNR table at the step 184. That is, the bandwidth of the channel is too low. However, in this case, the algorithm can continue by calculating a negative margin and simply proceeding to maximize the negative margin so that, although the BER that will be achieved will exceed the desired BER, it is still minimized given the requested data rate. In another embodiment, the algorithm can terminate at this point and indicate that the bits cannot be allocated. In yet another embodiment, the algorithm can be rerun using a higher BER and (presumable) lower minimum SNR requirements for the various constellation sizes.

If it is determined at the step 192 that N is not less than N_{max} (i.e., the system will be operating with a negative margin) then control transfers from the step 192 to a step 198 where the low-bound on the margin M_L, is set to zero. Following the step 198 is a step 200 where the high-bound on the margin is set using the formula $M_K = (10/J^*)(N_{max}-N)$. Note that, however, in this case the high-bound on the margin will be set to a positive value at the step 200 because N_{max} - N will be a positive number.

Following either the step 200 or the step 196, control transfers to a step 202 where the iteration counter that is used to terminate the algorithm after a predetermined number of iterations is set to one. Following the step 202, the initialization routine is

transmission errors. Following the step 266 is a step 268 where the receiver allocates various bits among the carriers using, in a preferred embodiment, the technique disclosed above in connection with Fig.'s 6 and 7.

Following the step 268 is a test step 270 which determines if the bit allocation table provided at the step 268 is different than the previous bit allocation table. That is, it is determined at the step 270 if there is a difference between the recently-calculated bit allocation table and the previous bit allocation table. If it is determined at the test step 270 that there is no difference (i.e., that the bit allocation table has not changed), then control transfers from the step 270 back to the step 262 where the software waits for the transmitter to send another reference frame. Otherwise, if it is determined at the step 270 that the new bit allocation table is different than the old bit allocation table, then control transfers from the step 270 to a step 272 where a flag is sent from the receiver to the transmitter indicating that the bit allocation table has changed. In a preferred embodiment, the flag is sent at the step 272 via a single carrier of the multicarrier signal that is reserved for use by the transmitter and receiver only for the flag. In another embodiment, the reserved carrier can also be used to transmit the new bit allocation table.

Following the step 272 is a step 274 where the receiver sends the new bit allocation table, determined at the step 268, to the transmitter. Following the step 274, control transfers back to the test step 262 to poll and wait for the transmitter to send another reference frame.

While the invention has been disclosed in connection with the preferred embodiments shown and described in detail, various modifications and improvements thereon will become readily apparent tot hose skilled in the art. Accordingly, the spirit and scope of the present invention is to be limited only by the following claims.

7. A multicarrier modulation system according to claim 6 in which at least one of said thresholds is set to zero.

8. A multicarrier modulation system according to claim 6 which includes means for terminating data allocation when the amount of data transmissible across said channels in accordance with previously specified signal to noise ratios associated with said channels equals the amount of data desired to be transmitted across said channels.

9. A multicarrier modulation system according to claim 6 which includes means for terminating data allocation when said difference diverges.

10. A multicarrier modulation system according to claim 6 which includes means for terminating data allocation after a defined number of iterations of margin calculations over said channels.

11. A multicarrier modulation system according to claim 1 in which said means for calculating trial noise margins comprises:

A. means for defining a trial margin that is a function of the difference between the amount of data allocable to said channels in accordance with said initial signal to noise ratios for the respective channels and the amount of data desired to be transmitted, and

B. means for repetitively adjusting said trial margin in accordance with the relation between the amount of data transmissible across said channels when the signal to noise ratios of said channels are augmented by said trial margin and the amount of data

C. transmissible across said channels in accordance with a prior determination of said signal to noise ratios.

amount of data transmissible over said channels with said augmented signal to noise ratios and the amount of data desired to be transmitted until an exit condition is reached.

15. A multicarrier modulation system according to claim 14 in which said exit condition comprises equality between the amount of data transmissible over said channels with a particular set of augmented signal to noise ratios and the amount of data desired to be transmitted.

16. A multicarrier modulation system according to claim 14 in which said exit condition comprises an increase in the difference between the amount of data transmissible over said channels with said augmented signal to noise ratios and the amount of data desired to be transmitted as determined on successive calculations.

17. A multicarrier modulation system according to claim 14 in which said exit condition comprises determination of a defined number of successive trial noise margins.

18. A multicarrier modulation system according to claim 14 which includes means for periodically transmitting a reference frame from the transmitter to the receiver across said channels, and means for measuring the signal to noise ratios of said channels from the transmitted reference frame, said means for calculating trial noise margins across said channels using the signal to noise ratios determined in the most recently transmitted frame as the initial signal to noise ratios for calculating said margins in the interval between said frame and the next frame.

23. A method according to claim 22 which further includes the steps of:

A. periodically transmitting a reference frame from the transmitter to the receiver across said channels,

B. measuring the signal to noise ratios of said channels from the transmitted reference frame and using the signal to noise ratios determined in the most recently transmitted frame as the signal to noise ratios for calculating said margins in the interval between said frame and the next frame.

24. A method according to claim 23 which includes the steps of providing first and second memory register sets at both said transmitter and said receiver for storing channel data allocations in accordance with signal to noise ratios associated therewith, and transmitting from the transmitter to the receiver a flag indicating which of the register sets is to be used for subsequently receiving data from said transmitter.

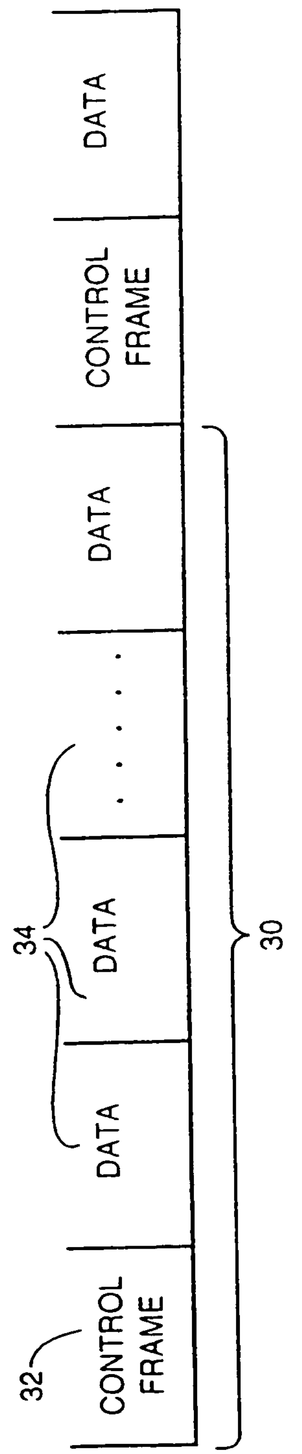


FIG. 2

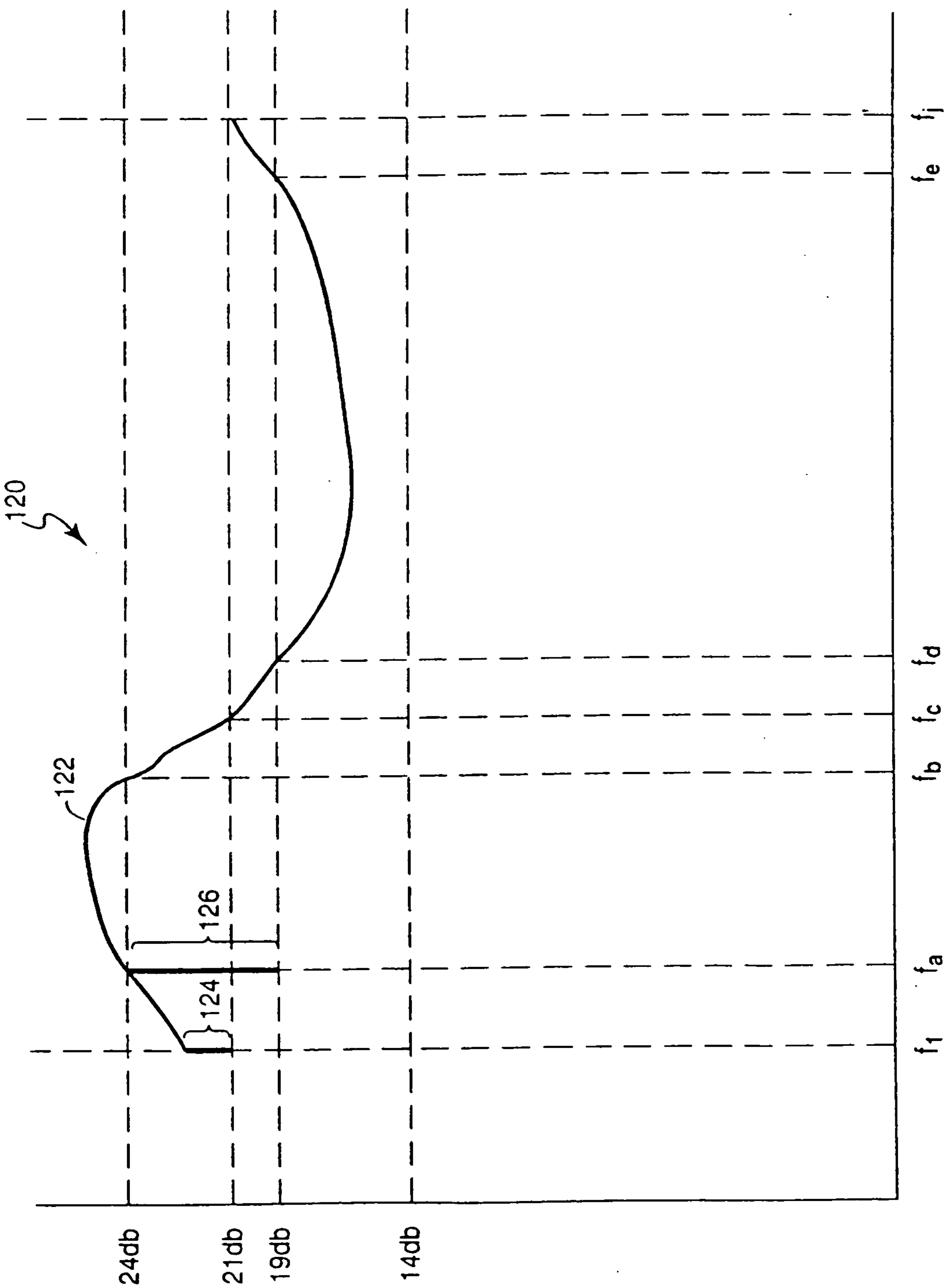
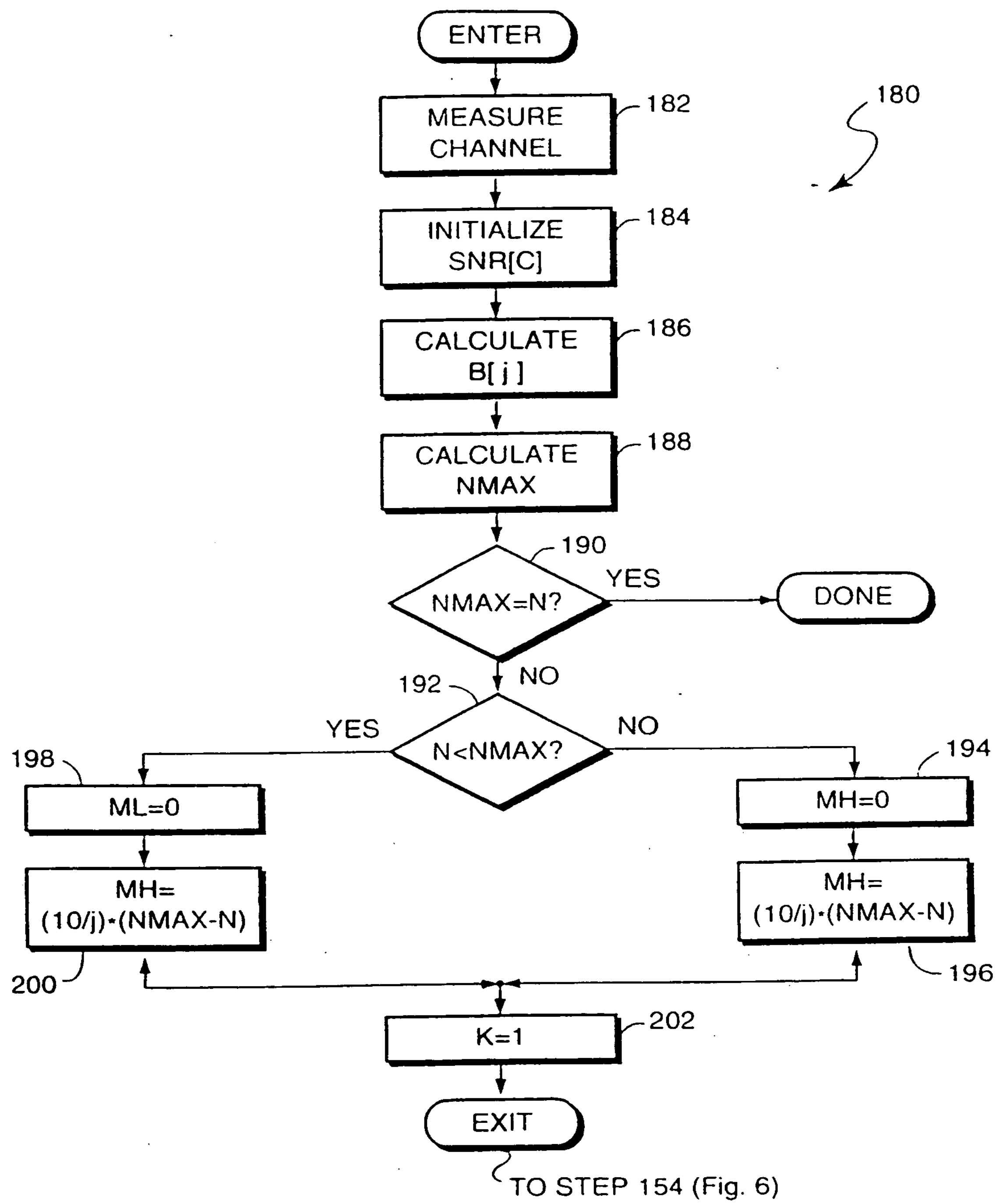


FIG. 5



ENTER
MEASURE CHANNEL
182
180
INITIALIZE SNR[C]
184
CALCULATE B[j]
186
CALCULATE NMAX
188
190
NMAX=N?
YES
DONE
NO
192
N<NMAX?
YES
NO
198
ML=0
194
MH=0
MH= (10/j)·(NMAX-N)
200
MH= (10/j)·(NMAX-N)
196
K=1
202
EXIT
TO STEP 154 (Fig. 6)

FIG. 7

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 98/11345

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H04L27/26

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H04L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No
X	EP 0 753 947 A (ALCATEL BELL NV) 15 January 1997 see column 6, line 39 - line 51 see column 11, line 49 - column 13, line 19 see claims 1-6,8 see figure 3 ---	1-24
A	US 5 479 447 A (CIOFFI JOHN M ET AL) 26 December 1995 cited in the application see column 3, line 57 - column 4, line 28 see column 5, line 42 - column 6, line 14 ---	1-24
A	WO 86 07223 A (TELEBIT CORP) 4 December 1986 cited in the application see page 17, line 12 - page 24, line 2 --- -/--	1-24

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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"&" document member of the same patent family

Date of the actual completion of theinternational search	Date of mailing of the international search report
12 November 1998	19/11/1998

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Koukourlis, S

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/US 98/11845

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